

# Parallel Neutrino Triggers using GPUs for an Underwater Telescope

*Bachir Bouhade<sup>1</sup>, Mauro Morganti<sup>1,2</sup>, Giuseppe Terreni<sup>1</sup>  
for the KM3Net-It Collaboration*

<sup>1</sup> INFN, Sezione di Pisa, Polo Fibonacci, Largo B. Pontecorvo 3, 56127 Pisa, Italy

<sup>2</sup> Accademia Navale di Livorno, viale Italia 72, 57100 Livorno, Italy

**DOI:** will be assigned

Graphics Processing Units are high performance co-processors originally intended to improve the use and the acceleration of computer graphics applications. Because of their performance, researchers have extended their use beyond the computer graphics scope. We have investigated the possibility of implementing online neutrino trigger algorithms in the KM3Net-It experiment using a CPU-GPU system. The results of a neutrino trigger simulation on a NEMO Phase II tower and a KM3-It 14 floors tower are reported.

## 1 Introduction

A neutrino telescope is a tool to increase our knowledge and to answer fundamental questions about the universe. Following the success of the IceCube experiment [1], which is a km<sup>3</sup> size telescope in the ice at the south pole, and of the ANTARES experiment [2], an underwater telescope with a volume of 0.4 km<sup>3</sup>. The European scientific community is going to construct a neutrino telescope similar to but larger than IceCube called Km3Net in the Mediterranean Sea. NEMO [3] and NESTOR [4] are R&D experiments for the same purpose. All these optical telescopes use a Photomultiplier Tube (PMT), or a group of it, as a Detection Unit (DU). The NEMO collaboration has already deployed a tower of 32 single PMT DUs. For the much larger Km3Net telescope, thousands of DUs will be used to detect the muon passage produced by undersea neutrino interactions. This large number of sensors will lead to a huge amount of data because of the presence of high rate background, and the data must be filtered by an efficient trigger algorithm to reduce the background rate and to keep all possible muon tracks. In the case of the ANTARES telescope, the amount of data acquired in a second is 0.3-0.5 GB, and a set of CPUs is used for such a task. The general strategy of data analysis for an online trigger is that a set of CPUs works in parallel on consecutive time slices within one second of the data coming from the underwater telescope [3]. In the present work, we describe the study of combining a Graphical Processor Unit (GPU) and CPU (GPU-CPU) to implement the muon trigger algorithms. In addition, the use of GPU-CPU leads to savings in power, hardware and time. The parallel version of the trigger algorithm is shown to be suitable for an online muon track selection and was tested on simulated data of the NEMO towers of 32 (NEMO Phase II) and 84 (KM3Net-It tower) single PMT DUs.

## 2 DAQ system of NEMO Phase II

During March 2013, the NEMO collaboration has deployed a tower (See Fig.1) at the Capo Passero site, south east of Sicily island [3]. Since then, it was taking data until August 2014, when it was shut-down for upgrades. The tower is 450 m high and it is composed of 8 floors, each floor is equipped with 4 DUs and two hydrophones. The distance between floors is 40 m, where the length of the floor is 6 m. The tower is kept straight by an appropriate buoyancy on its top.

The tower is hosted at a depth of 3400 m nearly 100 km off the Capo Passero harbor. Each floor is equipped with a Sea Floor Control Module (SFCM) that collects data streams from the four PMTs as well as the two hydrophones and sends it to its twin card on-shore called Earth FCM (EFCM). The communication between the SFCM and EFCM is guaranteed via an Electro-Optical-Cable (EOC) which permits 2.5 Gbs of bandwidth. During data acquisition and low bioluminescence activity, the measured rate by each PMT is 50-55 kHz. The PMT hit size is 28 bytes in average and 20% of the available bandwidth is used.

The data streams from all EFCMs are grouped into two streams and routed to the first stage of CPUs data processing called Hit Managers (HM) via Gbit link, which means the tower has two HMs as in Figure 2. Each HM merges together the 16 PMT data streams and divides them in consecutive time intervals of 200 ms called time-slices. All time slices from HMs within the same time interval are sent to one Trigger CPU (TCPU), where the trigger is applied. Successive time slices are sent to different TCPUs. A detailed description of the DAQ system can be found in [3]. Once trigger conditions are satisfied, a  $6\mu s$  time window of the tower data (centered at the time of the trigger seed) is sent to the Event Manager for storage. And last, another off-line filter is applied on the saved events for muon track reconstruction.

## 3 Muon trigger strategy

A muon passing through water, faster than the speed of light in that medium, produces Cherenkov photons. These photons have an angle  $\theta_C$  with respect to the trajectory of the muon and are detected by distributed DUs. The arrival times of Cherenkov photons at PMTs are correlated in time and space which is not the case for background photons (most photons are generated by  $^{40}K$  decays). Hence, looking for coincidences of multiple PMTs within a certain time window reduces the background rate.

In fact, the time difference of the arrival time of photons generated by a muon are distributed in a  $3\mu s$  (time needed for a muon to traverse the detector) interval or less. A time-space correlation between PMT hits within a time interval less than  $3\mu s$  can be used to filter out the background hits. In addition to the time-space correlation, a hit charge over threshold trigger can be applied on all hits. These types of triggers can be parallelized as they are applied on data streams independently.

Even though these triggers are simple, the amount of background hits in the NEMO phase II (8 floors tower) is about 1.7 Mhits/s/tower (comparing to roughly a few hits/s of a muon track) and it will be 4.6 Mhits/s for the 14 floors tower. In addition to these standard triggers, we have studied a new level 0 trigger algorithm. It is easy to implement on a GPU and is based on N hits in a fixed Time Windows TW, we chose  $N=7$  and  $TW=1000ns$  (N7TW1000). This trigger reduces the time-consuming of time-space correlation and charge over threshold triggers [5]. After this level 0 trigger, we apply the previously mentioned triggers, reducing the rate

drastically.

## 4 CPU-GPU

The aim of our work is to replace the TCPU by a TCPU-GPU system (TGPU). The work in the TGPU is done in three steps: first prepare 1s of data to be sent to GPU, then, send data to the GPU for trigger selection, and last, save the selected events.

Every PMT hit data point in the NEMO Phase II tower contains a header with the GPS time and geometry information, followed by a sampled charge waveform with a variable size. To apply triggers in the GPU, the raw hits are converted to a fixed size structure that contains all needed information for the trigger algorithms: charge, time, DU identification (DU\_ID), trigger flags, and rates. We have optimized the work in CPU and GPU to minimize the trigger searching time as explained in next paragraphs.

### 4.1 Preparation in CPU

The main work of the CPU is to convert 5 consecutive time slices of 200 ms to a unique time slice of 1 s to be sent to the GPU (one fixed-size memory buffer). This is done by running 5 threads in the CPU; each thread is filling the dedicated memory zone, which means that the 5 CPU threads are filling the same memory zone but at different offsets. Each thread converts the 200 ms time slice to  $N$  time slices to be used by GPU threads. The number of threads  $N$  is chosen to have in average 100 hits per thread at a nominal rate of 50 kHz/PMT. Hence, the total number of threads (NTHRD) in a GPU is  $NTHRD=5 \times N$ .

In our simulation code we have also taken into account the edge effect between threads. When the trigger algorithm reaches the last hit of the current thread, it proceeds on first hits of the next time slice. The data sent to the GPU is a 1 second time interval and its size takes into account the maximum rate of each PMT (5 times the nominal rate). Hence, with the NEMO tower of 84 PMTs and in the presence of bioluminescence at two PMTs, for example at rate of 1 Mhits/s, and assuming a nominal hit number per thread of 100 (55 kHz/PMT), we expect an increase of 40% (140 hits/thread) of the number of total hits.

### 4.2 Sorting and triggering in GPU

The work on the GPU side is done in two steps. First we sort the hits in time using classical sorting methods (Shell, quick, and merge sort algorithms). Then we apply the needed trigger algorithms (see the list below). Figure 3 shows the performance of quicksort and Shellsort algorithms on uniformly distributed time values. To see the effect of the hit structure size on the sorting time, the sorting algorithms are tested on hits of different sizes (one float is used for the time value). Clearly the quicksort algorithm shows a good performance and the measured times for all cases remain below 100 ms for 100 elements per thread. In addition, Figure 3 shows how the size of the hit structure affects the performance of the sorting algorithms.

In the case of NEMO tower data, we have noticed, that the Shellsort algorithm shows a better performance over the others. The reason for this is that our data within a GPU thread is not completely random, but is time-ordered for single PMT within a GPU thread.

After time sorting, we apply the following trigger algorithms:

- Time-space correlation (for NEMO Phase II tower):

- N7TW1000: looking for 7 hits in  $TW = 1000$  ns: `hit[i].time- hit[i+7].time < TW`
- DN7TW1000: looking for 7 hits from different PMTs within  $TW = 1000$  ns
- Simple Coincidence (SC): a coincidence between two hits occurred in two adjacent PMTs within 20 ns
- Floor Coincidence (FC): a coincidence between two hits occurred in two PMTs in the same floor within 100 ns
- Adjacent Floor Coincidence (AFC): a coincidence between two hits occurred in two PMTs located at two consecutive floors within 250 ns
- Charge threshold (QTRIG) looking for charge over a threshold: `hit[i].Charge > QTRIG`
- Combination of the above trigger seeds: for example applying N7TW1000, then SC and FC

N7TW1000 and DN7TW1000 have the same efficiency for muon track selection, however DN7TW1000 is more efficient in the presence of bioluminescence activities for background reduction [5]. In addition, the DN7TW1000 is time consuming and for this reason we have used N7TW1000 in our simulation. To select muon events we combine these trigger seeds. Once the candidate hits satisfy the trigger, all hits within  $\pm 3\mu s$  are tagged to be saved with respect to the time of one of the trigger seeds (in our simulation we have used the SC trigger). After that, the data is sent back to the CPU to save the tagged hits. Even though there is a difference in the rate of the selected events between applying N7TW1000 before or after time coincidences, we have chosen N7TW1000 first (as level 0 trigger) because the trigger time searching is less and the muon track selection efficiency remains the same [5].

## 5 Results and perspectives

For our simulation we have used a Tesla 20c50 (448 CUDA cores) and a GTX Titan (2688 CUDA cores) device. 2 PCs were used, one as a HM for time slice sending and the other PC was used with the GPU cards for the trigger algorithms. The measured time of the CPU to prepare 1 second of data ranges from 200 ms (for the 32 PMT tower) to 300 ms (for the 84 PMT tower), the CPU-GPU data memory transfer time is included. Our first aim was to see whether the TGPU can cope with data streaming and online triggering for muon track selection within the remaining time (less than 700 ms).

The first step was to simulate the actual NEMO Phase II tower with 32 DUs at a rate of 55kHz, applying the following triggers: charge trigger, SC, FC, AFC, N7TW1000, and a combination of them: applying N7TW1000, and if it is satisfied, we apply [SC and AFC] or [FC and AFC]. The last two triggers (N7TW1000 with [SC and AFC] or [FC and AFC]) are used to tag the muon track candidate. In the case of the KM3Net-It tower with 84 DUs, we use N7TW500 (the inter-floor distance is 20 m instead of 40 m).

Table (1) shows measured Tesla-GPU times for 1 second data from 32 and 84 PMTs using 8000, 20000, and 40000 threads, respectively, including the data preparation time on CPU (200-300 ms). We verify that the Tesla 20c50 GPU card is able to cope with the online trigger algorithms of the NEMO Phase II tower, as well as of KM3Net-It tower (with number of GPU threads  $\geq 20000$ ).

We have also compared the performance of our triggers between a Tesla 20c50 and a GTX Titan devices. We have tested only the GPU work without including the 1 second time slice preparing as well as data memory transfer. The results are shown in Table (2). We see that the measured trigger times, for Tesla 20c50, are less than the results shown in Table (1), because the CPU is not busy by the 1 second time slice preparation. For a sufficient number of GPU threads ( $\geq 2000$ ), both GPU cards can handle the online trigger with data of 84 PMTs. The measured trigger times can be used to give a first estimate of the speeding up of the trigger algorithm in the GPU over the CPUs.

The task of HMs can also be included in the CPU-GPU work, given that we were using only 40% of the CPU resources. HMs and TCPUs can be grouped in a TGPU system, with an adequate network structure. Our conclusion is that both GPU cards can be used in the TGPU system for the on-line muons trigger. We propose a new DAQ system based on TGPU structures (Figure 4) for the 8 towers of KM3Net-It, where each of the 8 TGPUs looks for all trigger seeds in a 1 second window of raw data of the corresponding tower and sends all trigger seeds to the TCPU for muon tracks selection. Once the TCPU selects the candidate trigger seeds for muon tracks, it sends back the corresponding times to all TGPUs to send their window of data to the Event Manger, and frees the corresponding memory buffer.

This new DAQ of the CPU-GPU is a huge simplification of the classical CPU DAQ system (using only CPUs) and can be used for both the online trigger and also the muon track reconstruction, by processing thousands of events at one step, and reducing further the fake events.

NTHRDs	32 PMTs (t/ms)	84 PMTs (t/ms)
8000	250	950
20000	230	600
40000	190	500

Table 1: Measured trigger times (ms) using Tesla 20c50 for 1 second time slice of NEMO towers data (time slice preparation on CPU is included).

## References

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NTHRDs	32 PMTs (t/ms)	84 PMTs (t/ms)
8000	160 / 90	500 / 450
20000	100 / 50	200 / 140
40000	50 / 45	150 / 110

Table 2: Measured trigger times (ms) using Tesla20c50 / GTX TITAN for 1 second of NEMO towers data without including the time preparation.

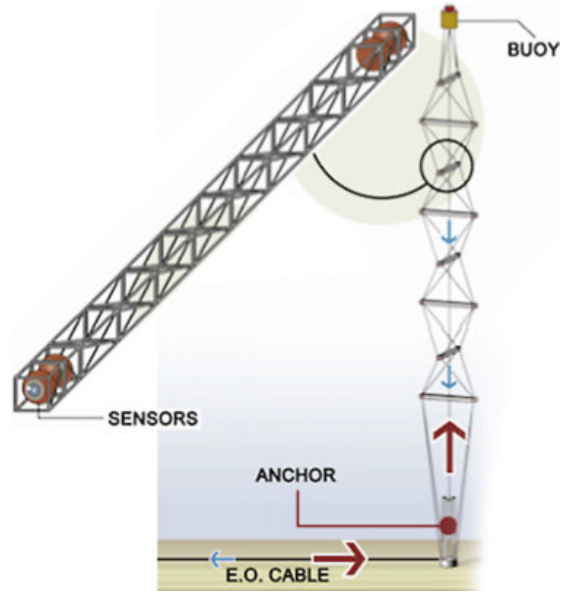


Figure 1: NEMO tower.

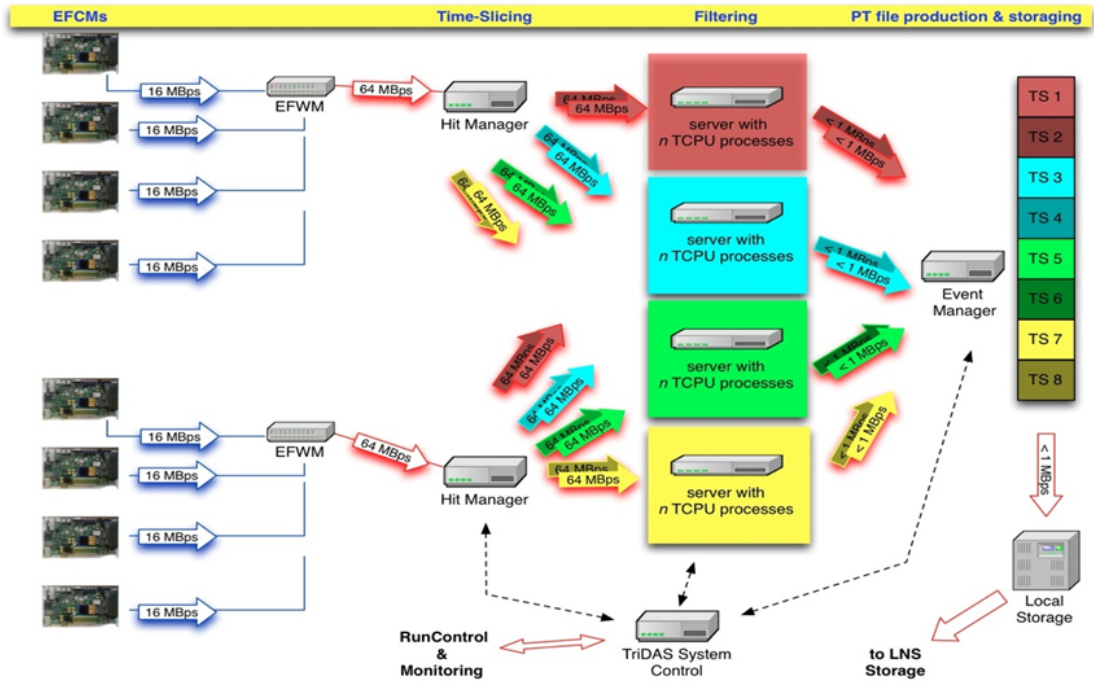


Figure 2: DAQ system for NEMO Phase II and the trigger scheme.

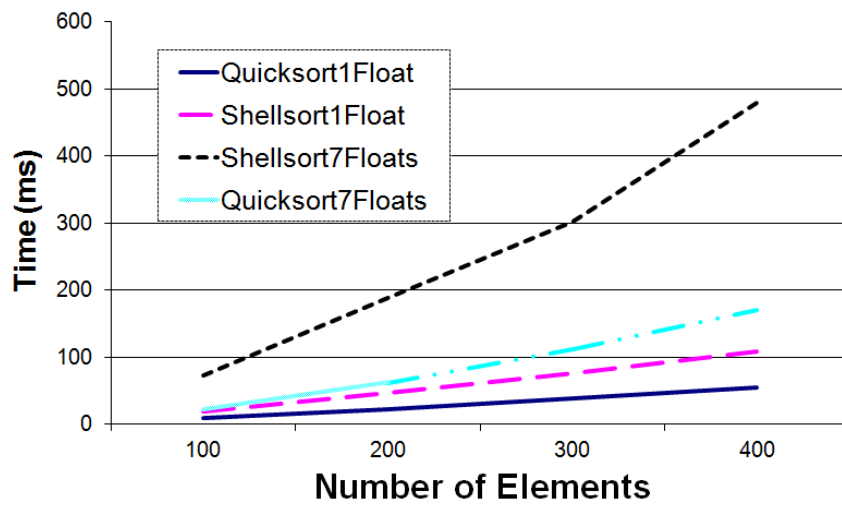


Figure 3: Measured sorting time (ms).

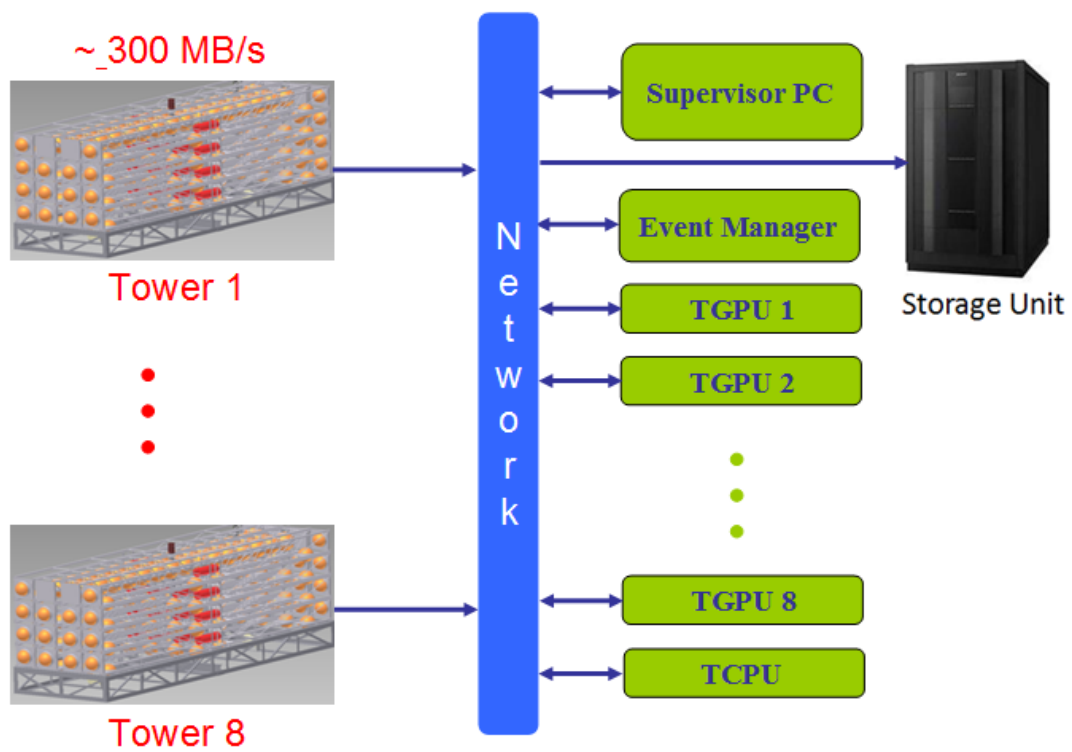


Figure 4: Proposed DAQ based on CPU-GPU structure.